

# Brookhaven Super-Neutrino Beam Scenario

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Representing Ideas of

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# Staging a Neutrino Factory

- Two feasibility studies for a Neutrino Factory have been concluded.
  - These studies indicate a cost of 2-2.5 B\$.
    - This *does not* include contingency and overhead.
    - This kind of money may not be available in the current climate
  - They indicate an optimistic turn-on date of 2012.
    - We might like to do some physics before that.
  - A staged approach to building a Neutrino Factory maybe desirable.
    - First Phase: Upgrade AGS to create a 1 MW *Proton Driver* and target station.
    - Second Phase: Build phase rotation and part of cooling system.
    - Third Phase: Build a pre-acceleration Linac to raise beam momentum to 2.5 GeV/c
    - Fourth Phase: Complete the Neutrino Factory.
    - Fifth Phase: Upgrade to entry-level Higgs Factory Muon Collider.
  - Each phase can support a physics program.

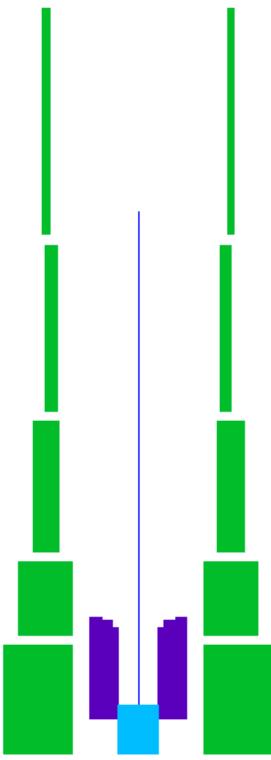
# First Phase Super Neutrino Beam

- Upgrade AGS to 1MW Proton Driver:

Machine	Power	Proton/Pulse	Repetition Rate	Protons/SSC year
Current AGS	0.17 MW	$6 \times 10^{13}$	0.625 Hz	$3.75 \times 10^{20}$
AGS Proton Driver	1 MW	$1 \times 10^{14}$	2.5 Hz	$2.5 \times 10^{21}$
Japan Hadron Facility	0.77 MW	$3.3 \times 10^{14}$	0.29 Hz	$9.6 \times 10^{20}$
Super AGS Prot Driver	4 MW	$2 \times 10^{14}$	5.0 Hz	$1.0 \times 10^{22}$
- Both BNL and JHF have eventual plans for their proton drivers to be upgraded to 4 MW.
- Build Solenoid Capture System:
  - 20 T Magnet surrounding target. Solenoid field falls off to 1.6 T in 30 m.
  - This magnet focuses both  $\pi^+$  and  $\pi^-$ . Beam will have both  $\nu$  and  $\bar{\nu}$
  - A solenoid is more robust than a horn magnet in a high radiation.
    - A horn may not function in the 4 MW environment.
    - A solenoid will have a longer lifetime since it is not pulsed.

# Solenoid Capture

Sketch of solenoid arrangement for  
Neutrino Factory →

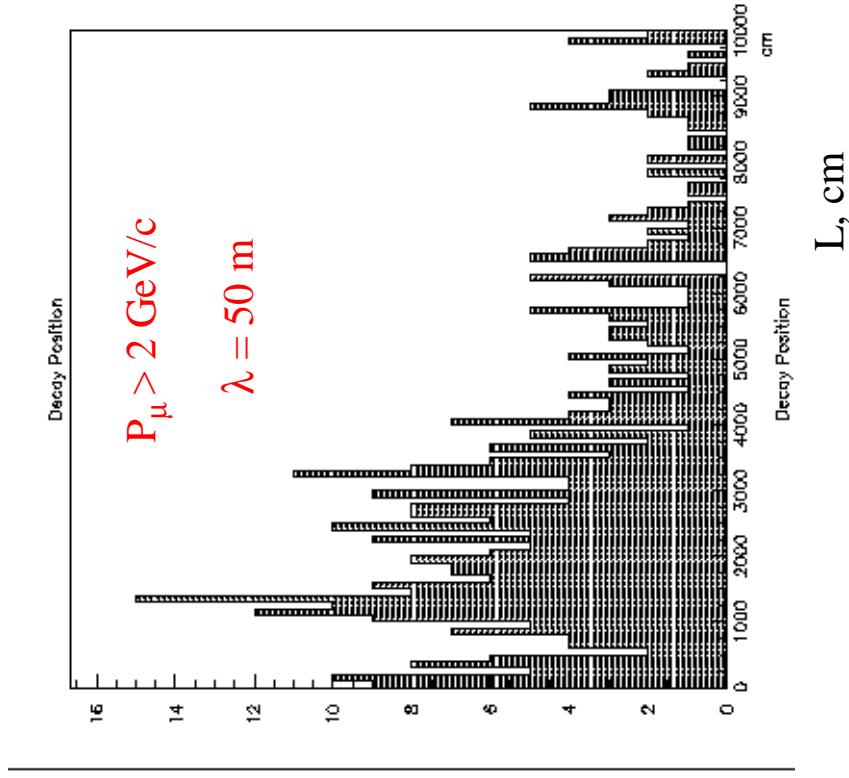
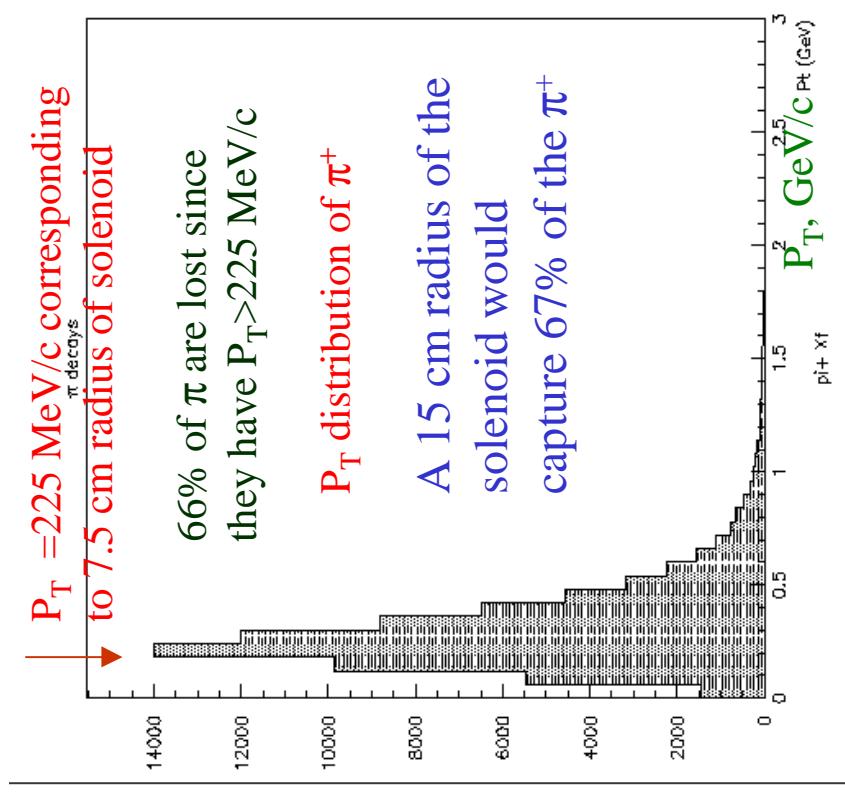


- If only  $\nu$  and not  $\bar{\nu}$  is desired, then a dipole magnet could be inserted between adjacent solenoids above.
- Inserting a dipole also gives control over the mean energy of the neutrino beam.
- Since  $\nu$  and  $\bar{\nu}$  events can be separated with a modest magnetic field in the detector, it will be desirable to collect both signs of  $\nu$  at the same time.

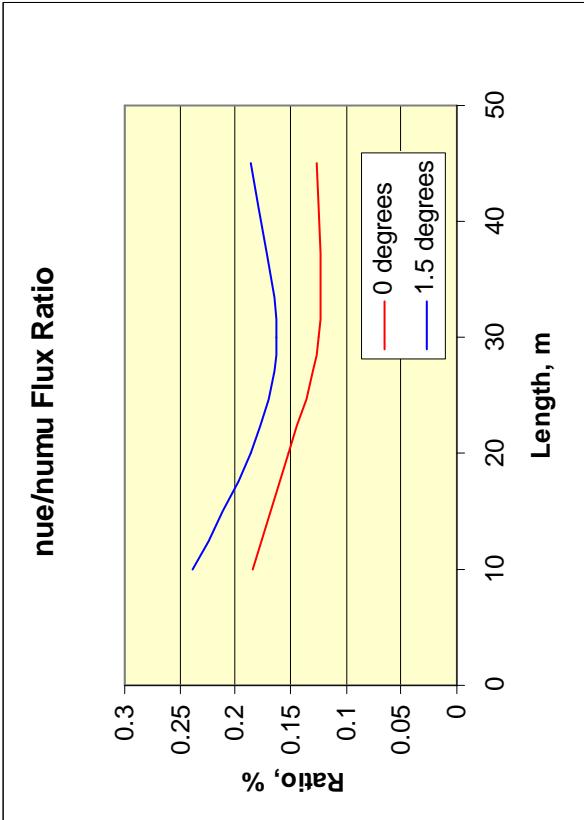
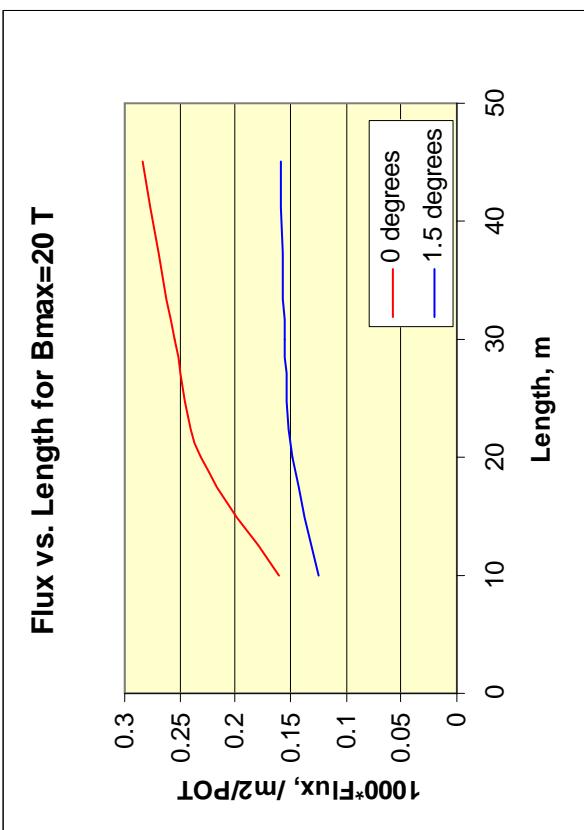
# Solenoid Design Simulation

- Model Solenoid Magnet in GEANT.
  - Use Geant/Fluka option for the particle production model.
  - Use 30 cm Hg target ( 2 interaction lengths.)
    - No target inclination.
      - We want the high momentum component of the pions.
      - Re-absorption of the pions is not a problem.
    - Field profile on axis is  $B(z)=B_{\max}/(1+a z)$ 
      - Independent parameters are  $B_{\max}$ ,  $B_{\min}$  and the solenoid length, L.
  - Pions and Kaons are tracked through the field and allowed to decay.
  - Fluxes are tallied at detector positions.
    - The following plots show  $\nu_\mu$  flux and  $\nu_e / \nu_\mu$  flux ratios.

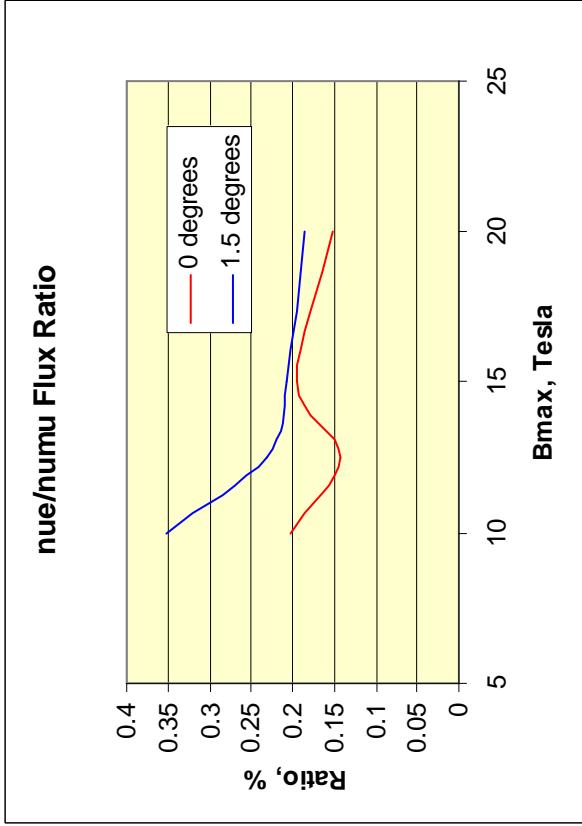
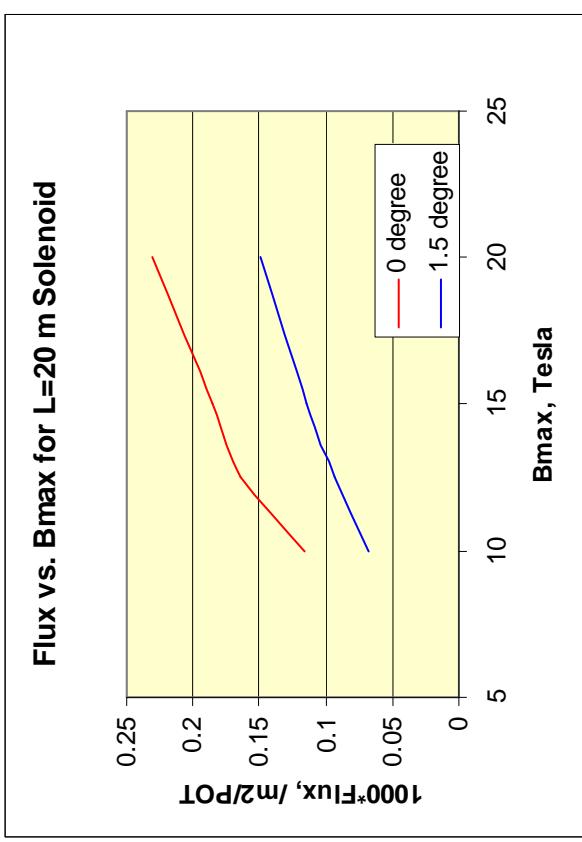
# Captured Pion Distributions



# Flux as a function of Solenoid Length

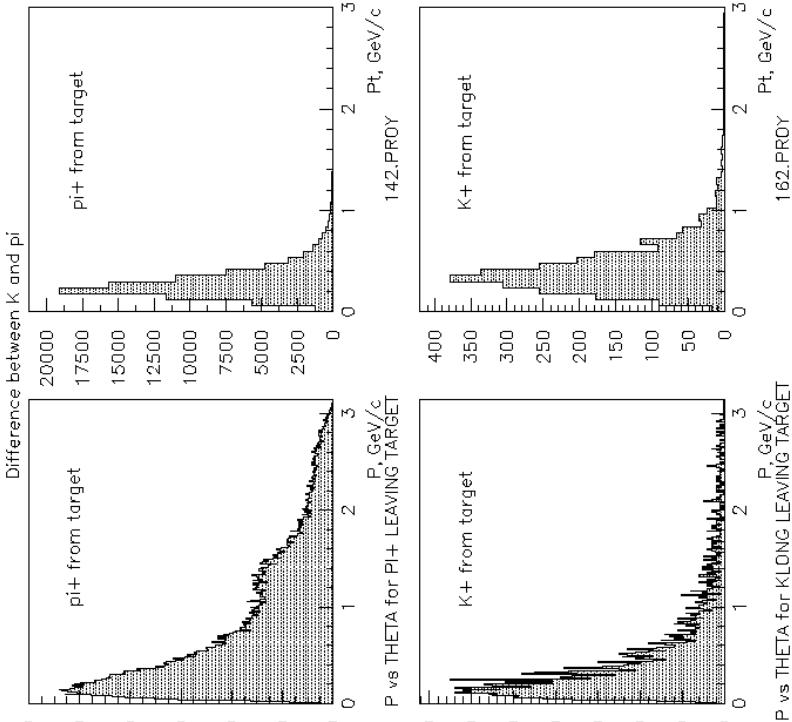


# Flux as a Function of Capture Field



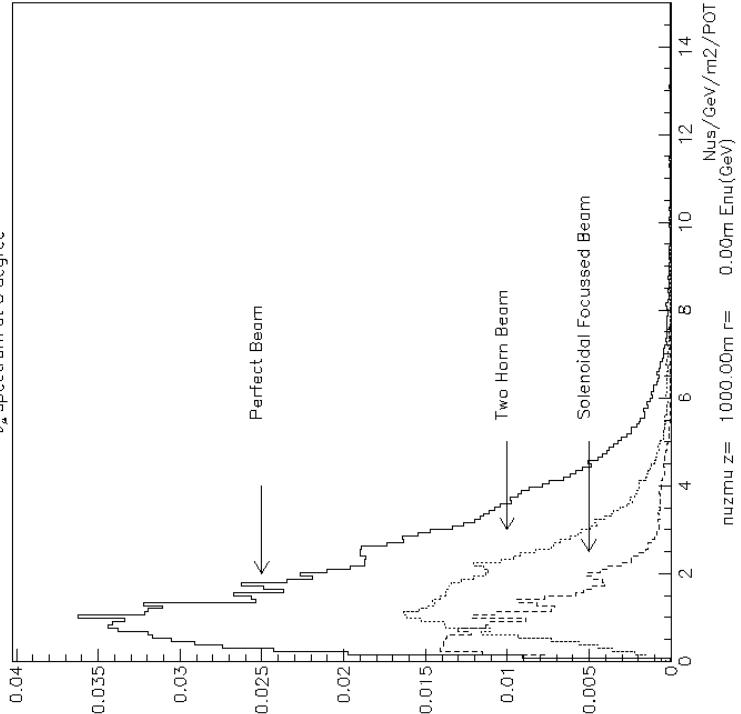
# $\nu_e/\nu_\mu$ Ratio

- The solenoid capture system sees a smaller  $\nu_e/\nu_\mu$  flux ratio than traditional horn systems.
  - We see  $\nu_e/\nu_\mu \approx 0.15\%$  as opposed to the 0.8% in horn beams.
- The solenoid captures a lower  $E_{\nu}$  spectrum.
- The  $P_T$  of the  $K^+$  are larger than that of the  $\pi^+$ .
  - This can explain only part of it.
- The  $\pi$  distribution is more forward in the center of mass than the  $K$  distribution.



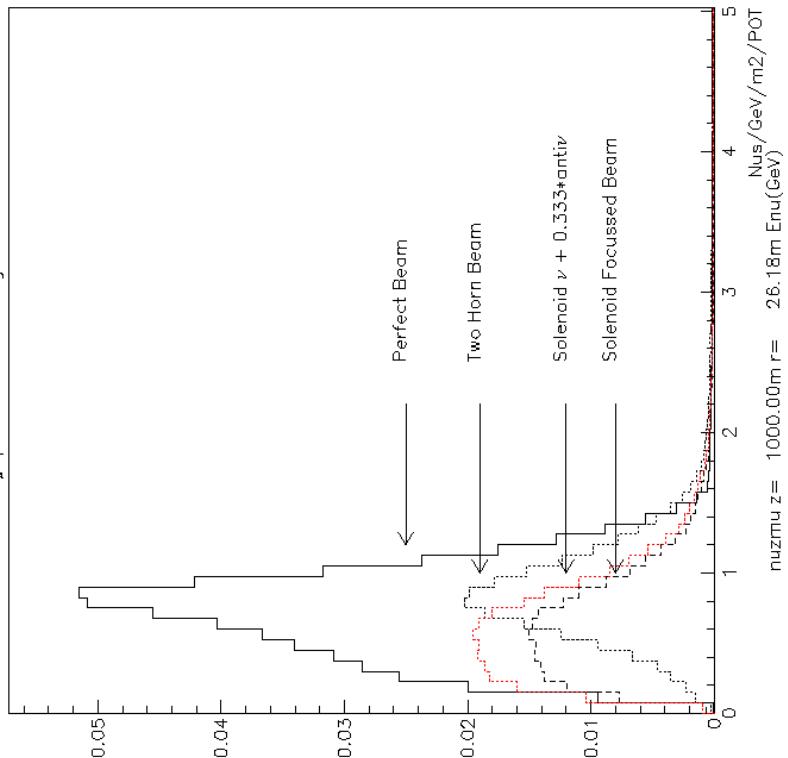
# Comparison of Horn and Solenoid Focused Beams

- The Figure shows the spectra at  $0^\circ$  at 1 km from the target.
  - Solenoid Focused Beam.
  - Two Horned Focused Beam designed for E889.
  - So-called *Perfect Focused* beam where every particle leaving the target goes in the forward direction.
    - The perfect beam is not attainable.  
It is used to evaluate efficiencies.
- A solenoid focused beam selects a lower energy neutrino spectrum than the horn beam.
  - This may be preferable for CP violation physics



# Horn and Solenoid Comparison (cont.)

- This figure shows a similar comparison of the 1 km spectra at 1.25° off axis.
  - The off axis beam is narrower and lower energy.
- Also a curve with the  $\nu$  flux plus 1/3 the anti- $\nu$  flux is shown in red.
- Both signs of  $\nu$  are focused by a solenoid capture magnet.
  - A detector with a magnetic field will be able to separate the charge current  $\nu$  and anti- $\nu$ .

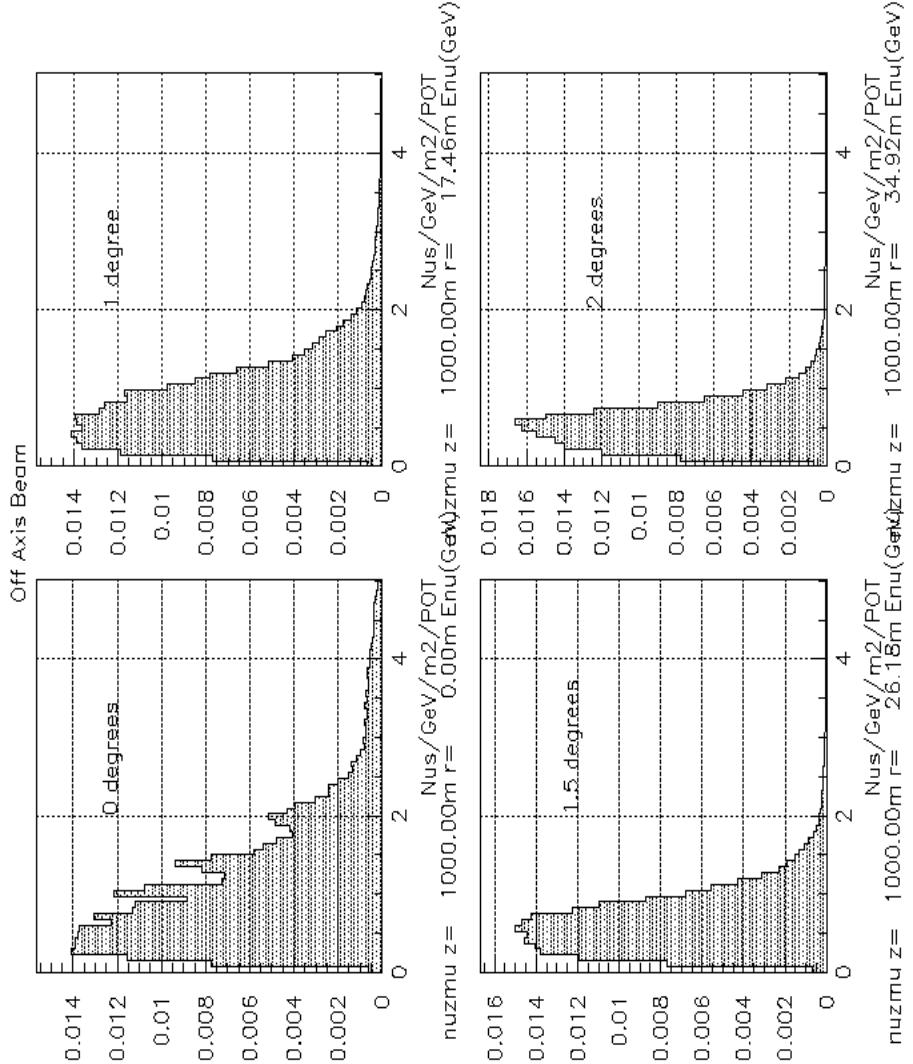


# $\nu$ Flux Seen at Off-Axis Angles

- We desire to have *Low Energy*  $\nu$  beam.

- We also desire to have a narrow band beam.

- I have chosen  $1.5^\circ$  off-axis for the calculations.



# Detector Choices

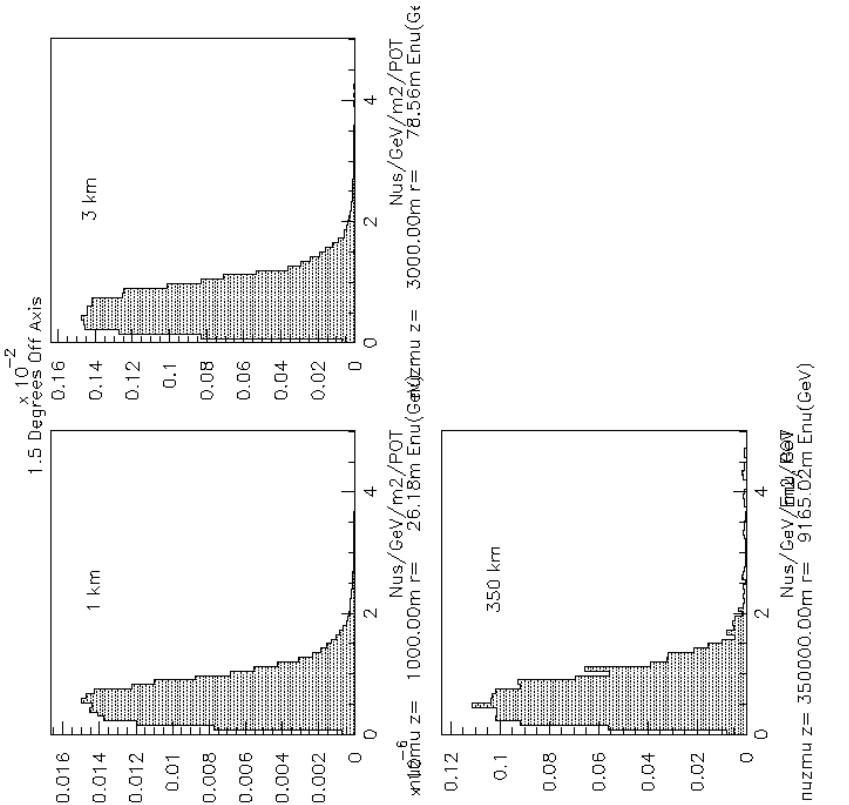
- The far detector would be placed 350 km from BNL (near Ithica, NY).
  - There are salt mines in this area. One would put the detector 600 m below ground.
- We are favoring Liquid Ar TPC similar to *Icarus*. The far detector would have 50 ktons fiducial volume (65 kttons total.)
  - Provides good electron and  $\pi^{\circ}$  detection.
  - The detector will sit between dipole coils to provide a field to determine the lepton charge.
- Close in 1 kton detectors at 1 km and/or 3 km.
  - 1 km detector gives  $\nu$  beam alignment and high statistics for detector performance.
  - 3 km detector is far enough away that  $\nu$  source is a point.

# Detectors Are Placed 1.5° Off ν Beam Axis

- Placing detectors at a fixed angle off axis provides a similar  $E_\nu$  profile at all distances.
- It also provides a lower  $E_\nu$  distribution than on axis.
- $\mu$  from  $\pi$  decays are captured by long solenoid channel. They provide low  $E_\nu$  enhancement.
- Integrated flux at each detector:

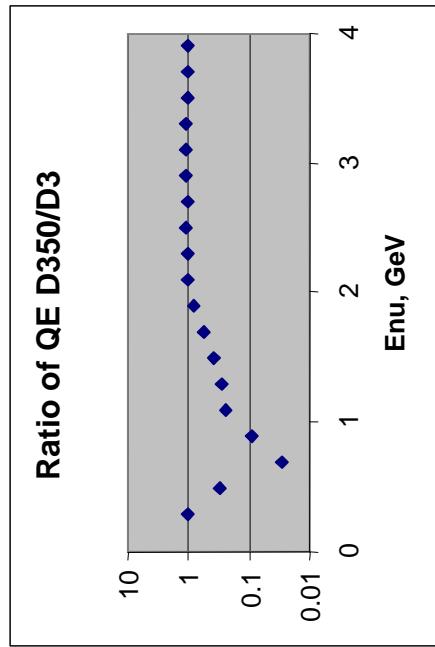
– Units are  $\text{ν/m}^2/\text{POT}$

Detector Position	$\nu_u$	$\text{Anti } \nu_u$	$\nu_e$	$\text{Anti } \nu_e$
At 1 km	$1.40 \times 10^{-5}$	$1.22 \times 10^{-5}$	$2.40 \times 10^{-8}$	$1.33 \times 10^{-8}$
At 3 km	$1.49 \times 10^{-6}$	$1.30 \times 10^{-6}$	$2.42 \times 10^{-9}$	$1.31 \times 10^{-9}$
At 350 km	$1.10 \times 10^{-10}$	$9.39 \times 10^{-11}$	$1.78 \times 10^{-13}$	$9.62 \times 10^{-14}$



# Neutrino Oscillation Physics

- The experiment would look at the following channels:
  - $\nu_\mu$  disappearance -- primarily  $\nu_\mu \rightarrow \nu_\tau$  oscillations.
    - Sensitive to  $\Delta m_{23}^2$  and  $\Theta_{23}$
    - Examine ratio of  $\nu n \rightarrow \mu p$  (QE) at 350 km detector to 3 km detector as a function of  $E_\nu$ .
  - $\nu N \rightarrow \nu \pi^0 N$  events
    - These events are insensitive to oscillation state of  $\nu$
    - Can be used for normalization.
  - $\nu_e$  appearance
    - (continued on next transparency)



# $\nu_e$ Appearance Channel

- There are several contributions to  $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ :
    - Solar Term:  $P_{\text{solar}} = \sin^2 2\theta_{12} \cos^2 \theta_{13} \cos^2 \theta_{23} \sin^2 (\Delta m_{\text{sol}}^2 L / 4E)$ 
      - This term is very small.
    - Tau Term:  $P_\tau = \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 (\Delta m_{\text{atm}}^2 L / 4E)$ 
      - This is the dominant term.
    - Terms involving the CP phase  $\delta$ :
      - There are both CP conserving and violating terms involving  $\delta$ .
      - The CP violating term can be measured as
- $$A_{CP} = \frac{P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}{P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) + P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)} \approx \frac{\Delta m_{12}^2 L}{4 E_\nu} \frac{\sin 2\theta_{12}}{\sin \theta_{13}} \sin \delta$$
- This asymmetry is larger at lower  $E_\nu$ . This could be ~25% of the total appearance signal at the optimum  $E_\nu$
  - The 4 MW proton driver would be necessary for this asymmetry

# Event Estimates Without Oscillations

- Below is shown event estimates expected from a solenoid capture system
  - The near detectors are 1 kton and the far detector is 50 kton.
  - The source is a **1 MW** proton driver.
  - The experiment is run for **5 Snowmass years**. This is the running period used in the JHF-Kamioka neutrino proposal.
  - These are obtained by integrating the flux with the appropriate cross sections.

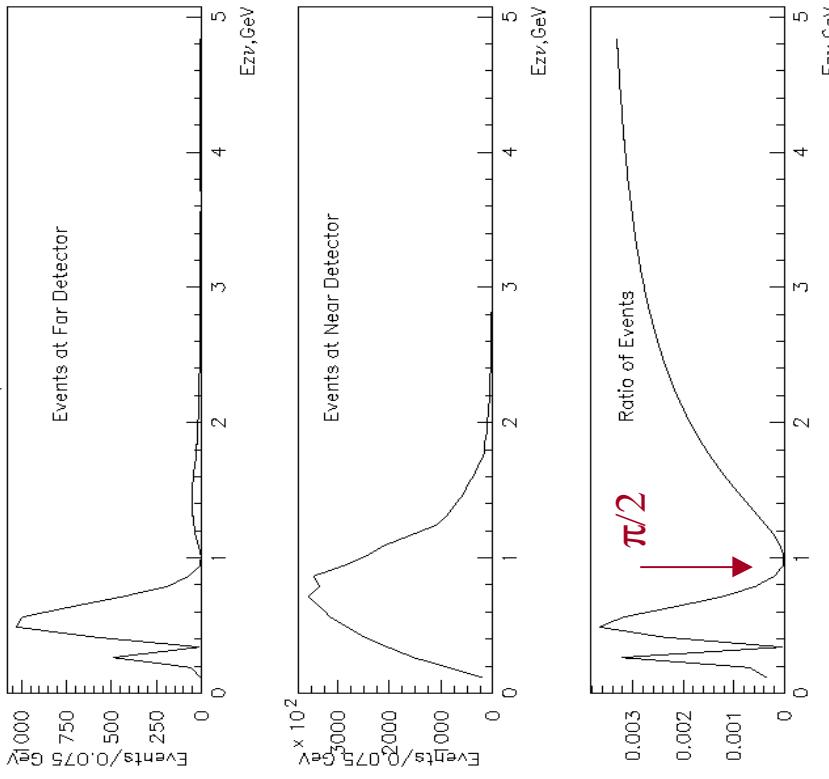
Detector Position	$\nu_\mu n \rightarrow \mu^- p$	$\nu_\mu p \rightarrow \mu^+ n$	$\nu N \rightarrow \nu N \pi^0$	$\nu_e n \rightarrow e^- p$	$\nu_e p \rightarrow e^+ n$
At 1 km	$3.87 \times 10^7$	$8.82 \times 10^6$	$3.87 \times 10^6$	$9.95 \times 10^4$	$14978$
At 3 km	$4.17 \times 10^6$	$9.44 \times 10^5$	$4.28 \times 10^5$	$1.00 \times 10^4$	$1477$
At 350 km	15539	3455	1618	36.7	5.4

- Estimates with a **4 MW** proton driver source would be four times larger.

# Determination of $\Delta m^2_{13}$

- Consider a scenario where
  - $\Delta m^2_{12} = 5 \times 10^{-5} \text{ eV}^2$
  - $\Theta_{23} = \pi/4$
  - $\Delta m^2_{31} = 0.0035 \text{ eV}^2$  (unknown)
  - $\sin^2 2\Theta_{13} = 0.01$  (unknown)
  - This is the Barger, Marfatia, and Whisnant point Ib.
- $\langle E_\nu \rangle = 0.8 \text{ GeV}$  is *not* optimum since I don't know the true value in advance.
- I can determine  $\Delta m^2_{13}$  from
 
$$1.27 \Delta m^2_{13} L / E_0 = \pi/2$$

Where  $E_0$  is the corresponding null point



# Barger, Marfatia and Whisnant Table

TABLE II. Scenarios with  $\delta m_{31}^2 > 0$  (2 years  $\nu_e$ , 6-12 years  $\bar{\nu}$ ); the last entry in the table shows the results for JHF-SK [11] (5 years,  $\nu$  only).  $\theta_{23} = \pi/4$  is assumed.

$\delta m_{31}^2$ (eV $^2$ )	$\delta m_{31}^2$ (eV $^2$ )	L (km)	E (GeV)	$\{N_\nu\}_{\sin^2 2\theta_{13} = 0.01}$	$B_\nu$	$N_\tau$	$\sin^2 2\theta_{13}$ reach at $\Sigma_\tau$ $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	$\log(\delta m_{31}^2)$	$ \delta (^*)$ at $\Sigma_\tau$ $\sin^2 2\theta_{13} = 0.01$
$5 \times 10^{-3}$	$2 \times 10^{-3}$	850	0.57	180	148	116	-	0.0030	-
		750	1.18	95	63	56	-	0.0036	0.10
		1290	2.09	64	27	32	-	0.0031	0.036
		1770	2.86	58	15	23	-	0.0033	0.014
		28900	4.70	39	4	14	10	0.0038	0.020
								0.055	0.011
								-	-
	$8.5 \times 10^{-3}$	850	0.99	283	287	204	-	0.0034	0.0039
		750	2.07	156	100	97	-	0.0036	0.0043
		1290	3.65	106	42	55	14	0.0037	0.015
		1770	5.01	88	22	40	36	0.0028	0.012
		28900	8.23	67	5	23	51	0.0039	0.045
								0.045	0.0037
								-	-
	$5 \times 10^{-2}$	850	1.41	412	331	289	-	0.0034	0.0030
		750	2.96	219	189	189	-	0.0035	0.0040
		1290	5.21	150	57	79	77	0.0025	0.0066
		1770	7.16	125	39	58	100	0.0025	0.0095
		28900	11.74	95	7	35	103	0.0025	0.0061
								0.036	0.0041
								-	-
	$10^{-4}$	$2 \times 10^{-3}$	850	0.57	283	201	116	-	-
		750	1.18	120	88	56	-	0	-
		1290	2.09	78	41	33	-	0.0007	0.10
		1770	3.86	62	24	23	-	0.0014	0.055
		28900	4.70	44	9	14	10	0.0025	0.023
								-	-
								-	-
	$8.5 \times 10^{-3}$	850	0.99	324	268	204	-	0.0018	0.0016
		750	2.07	170	114	97	-	0.0017	-
		1290	3.65	114	50	55	14	0.0030	0.0053
		1770	5.01	91	28	40	36	0.0022	0.0092
		28900	8.23	69	8	25	51	0.0025	0.037
								0.010	0.010
								-	-
	$5 \times 10^{-2}$	850	1.41	433	353	289	-	0.0018	0.0023
		750	2.96	229	149	139	-	0.0030	0.0053
		1290	5.21	148	55	79	77	0.0031	0.0056
		1770	7.16	129	81	58	100	0.0022	0.0093
		28900	11.74	96	9	35	102	0.0028	0.0053
								-	-
	$8 \times 10^{-3}$	285	0.7	12	-	23	-	0.016	-
								-	-

# Oscillation Signal

Table 1: Oscillation Signal:

- Consider  $\Delta m^2_{12}=5\times 10^{-5} \text{ eV}^2$ ,  $\theta_{23}=\pi/4$  and  $\sin^2 2\theta_{13}=0.01$
- Using a 1 MW proton driver and a 50 kton detector 350 miles away.
- Experiment running for  $5\times 10^7$  seconds.
- Solenoid capture system with  $\nu_e/\nu_\mu$  flux ratio=0.15 %

$\Delta m^2_{13} \text{ eV}^2$	$\nu_u$	$\nu_e$ signal	$\nu_e$ background	Anti $\nu_u$	Anti $\nu_e$ signal	Anti $\nu_e$ BG
No Oscillation	15539		37	3455		5.4
0.002	5065	76	37	1096	18.5	5.4
0.0035	5284	70	37	1283	16.2	5.4
0.005	7722	55	37	1762	13.1	5.4

- For comparison we have 28% of the flux used in Barger et al.
- We use a not necessarily optimum L/E fixed configuration for all cases.
- We use an actual flux distribution, not a monochromatic  $\nu$  beam (as used in Barger et al.).
- We see a quite significant appearance signal.

# Cosmic Ray Background

- This table shows the cosmic ray rates for a detector placed on the surface.
  - The rate reduction factors come from the E889 proposal.
  - The events shown are scaled to the 350 km detector mass and 5 Snowmass year running period.

	Muons	Neutrons
Raw Rate (kHz)	81.7	2.7
Beam Time Correlation Reduction	$2.5 \times 10^{-7}$	$2.5 \times 10^{-7}$
Passive/Active Shielding	0.001	0.18
Energy Cuts	0.47	0.26
Vertex and Direction Info	0.0033	0.062
Total Reduction	$3.9 \times 10^{-13}$	$7.2 \times 10^{-10}$
Background in $5 \times 10^7$ sec	34	2280

- The detector will be placed 600 m below ground in a mine.
  - The residual cosmic ray background would be ~0.002 events.

# Backgrounds to $\nu_e$ Appearance Signal

- The largest backgrounds to the  $\nu_\mu \rightarrow \nu_e$  signal are expected to be:
  - $\nu_e$  contamination in the beam.
    - This was  $\sim 0.15\%$   $\nu_e/\nu_\mu$  flux ratio in the capture configuration that was used in this study. This yields a 0.25% in the event ratio.
  - Neutral Current  $\nu\pi^0 N$  events where the  $\pi^0$  are misidentified as an electron.
    - If a  $\gamma$  from the  $\pi^0$  converts close to the vertex (Dalitz decay) and is asymmetric.
    - The magnetic field and  $dE/dx$  will be helpful in reducing this background. Simulation study is necessary.
    - I estimate (guess) that this background is  $\sim 0.001$  of the  $\nu\pi^0 N$  signal.

# Conclusions

- A high intensity neutrino super beam maybe an extremely effective way to study neutrino oscillations.
  - In particular the 4 MW version of the super beam may be the only way to observe CP violation in neutrino oscillations without a *Muon Ring Neutrino Factory*.
- This experiment is directly competitive with the JHF-Kamioka neutrino project.
  - Do we need two such projects? I will not answer that!